

POINTING AND TRACKING CONCEPTS FOR DEEP SPACE MISSIONS

J.W. Alexander, S. Lee, C. Chen
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

ABSTRACT

This paper summarizes part of a FY1998 effort on the design and development of an optical communications (Opcomm) subsystem for the Advanced Deep Space System Development (ADSSD) Project. This study was funded by the JPL X2000 program to develop an optical communications (Opcomm) subsystem for use in future planetary missions. The goal of this development effort was aimed at providing prototype hardware with the capability of performing uplink, downlink, and ranging functions from deep space distances. Such a system was envisioned to support future deep space missions in the Outer Planets/Solar Probe (OPSP) mission set such as the Pluto express and Europa orbiter by providing a significant enhancement of data return capability.

A study effort was initiated to develop a *flyable engineering model* optical terminal to support the proposed *Europa Orbiter* mission – as either the prime telecom subsystem or for mission augmentation. The design concept was to extend the prototype lasercom terminal development effort currently conducted by JPL's Optical Communications Group. The subsystem would track the sun illuminated Earth at Europa and farther distances for pointing reference.

During the course of the study, a number of challenging issues were found. These included thermo-mechanical distortion, straylight control, and pointing. This paper focuses on the pointing aspects required to locate and direct a laser beam from a spacecraft (S/C) near Jupiter to a receiving station on Earth.

1. INTRODUCTION

The goal of this effort was to develop a prototype engineering model optical communications (Opcomm) subsystem for future deep space missions requiring high rate downlink. Using the Europa Orbiter mission parameters as a reference, a baseline subsystem design concept was developed, taking into account the mission coverage, dynamic range, and operational requirements for communications and beam pointing. This paper addresses problems associated with the pointing issues required to direct a laser beam to an Earth receiving station.

The baseline Opcomm subsystem design employs a 30-cm diameter, diffraction-limited SiC telescope to support optical downlink data rate of 60 kbps and 200 kbps for daytime and nighttime reception, respectively. The Opcomm subsystem is designed to achieve these data rates at a limiting Sun-spacecraft-Earth angle of 2 degrees. At Europa, a 2 degrees SPE angle limit leads to a link outage of less than 28 days for conjunction, and 20 days for opposition. The current-best-estimate of mass and power consumption for the subsystem are 23 kg and 50 W, respectively. The mass estimate includes redundant transmitters, detectors, and beam steering elements.

The two key issues for pointing are knowledge of where the Earth receiving station is relative to the S/C, and then directing the downlink beam to the receiving station. The subsystem design allows using either an uplink laser beacon or with broadband celestial images to derive the receiving station location. The baseline pointing and tracking approach is to perform Earth Image tracking with occasion calibration using the Earth-moon or Earth-star images. At high phase angles when the Earth image does not provide sufficient brightness for high rate tracking, inertial sensors (accelerometers) measurements are used to propagate pointing knowledge at a higher rate in between celestial reference updates. Control of a steering mirror is maintained by closed-loop control of a portion of the downlink reflected to second detector.

Additionally, uplink beacon tracking may be required to support pointing at short range and during opposition when the Earth image alone does not provide sufficient signal power for tracking.

Earth image tracking is also desirable because of its high brightness (over most of the orbital period) and angular proximity of Earth intensity centroid to the receiver location. Uplink beacon tracking is an attractive alternative, although ground-based beacon uplink cannot provide the power required for high rate pointing without needing additional inertial-sensors. Furthermore, at low Sun-Earth-spacecraft angle when the Earth image is brightest, the Earth background can cause a shift in the measured beacon centroid and interfere with beacon tracking. Finally, by requiring a clear path for uplink in addition to clear downlink path, beacon-based system has a lower overall link availability.

Among the challenges of Earth image tracking include the unknown Earth albedo variation due to cloud coverage and the solar stray light. The baseline design answers the albedo variation problem by performing periodic imaging of the Earth with other celestial references -- such as the moon or nearby stars. These sources have well defined intensity pattern that allow accurate measurements of their position, but require long integration times. The position of Earth can then be calibrated using the measured celestial references' position and the known Earth ephemeris to determine correction offset.

Because during the mission, the Sun-spacecraft-Earth (SPE) angle becomes small, stray light control is important. At the low SPE angle, the subsystem is intended to operate (2 degrees from Sun), both optical surface quality and cleanliness need to be controlled to ensure low scattering of incident sunlight. The study suggests that the required surface quality for the mirror can be achieved. In addition, the optical design incorporates both a field stop in the telescope and a Lyot stop in the post secondary optics to control out of field scattered sunlight.

The study concluded that the operational requirements and design of a deep space optical communications subsystem are different from that of a near-Earth optical communications subsystem. Significant challenges on laser efficiency, thermal control, stray/scatter light control, and subsystem mass/power, in addition to the pointing and tracking discussed here need to be addressed for a successful subsystem implementation. However, with the exception of radiation hardness issues, it is thought that the design baseline presented in this document can achieve the desired functional objectives.

1. SYSTEM REQUIREMENTS AND REQUIREMENT DRIVERS

For the X2000 development JPL's traditional method of setting Level 1/ Level 2 system requirements was not applied because of the lack of a well-defined set of development objectives (e.g. mission requirements). Because of the large trade space available to the designer, one can easily choose to optimize the design in one aspect and ignore the other problems. An example of this is the flight-ground trade-off. One can require a larger aperture and higher power on the ground and simplify the flight system design. As a result, a set of requirements was developed for the Europa mission that took into account all the factors that could be identified.

The optical communications technology, which is sensitive to background radiation and pointing loss, will require some adjustment in the operational methodology and mission planning process, both of which cannot be performed without the mission input. However, past experiences in operating a RF link can lead to certain expectations of the link, which we shall attempt to maintain.

2. Limitation and Constraints of an Optical Link

Although optical communications system offer many potential advantages in deep space data return capability, the current implementation also has a number of limitations that can affect the link availability and overall data return strategy. These limitations are

1. **Limited Solar Conjunction availability:** This limit is imposed by the sun-spacecraft-Earth geometry as well as by the Sun-Earth-spacecraft geometry, which contributes straylight. In addition to the effect of increase background noise at Earth receiver, at small Sun-Probe-Earth (SPE) angles, the spacecraft's pointing and tracking detector will experience an increase in background noise due to the photon-noise in the straylight from the sun, leading to an increase in pointing error and, at worst case, inability to detect the Earth image or uplink beacon signal. This is discussed in more detail in CCHEN.

2. Weather-related availability. This limit is caused primarily by the limited clear weather probability from any ground stations. Furthermore, it also imposed restriction on ground station hand-offs and flight-ground coordination if a cooperative beacon tracking scheme is used. Atmospheric availability due to cloud coverage is a significant issue for optical communication systems.

3. Optical Link Characteristics

The key goals are to provide good mission coverage by being able to operate over the needed mission distances. An operational optical downlink will most likely need to cover most of the mission phases from shortly after launch to end of mission. Finally, prime mission coverage for deep space mission will generally require downlink from various link distances. For example, a Mars mission can have a link distance ranging from 0.5 to 2.7 AU, a Jupiter mission 4.2 to 6.2 AU while in orbit.

4. Reference Mission Requirements

For purposes of scaling the system throughput and mission coverage requirements, a baseline trajectory for an Earth-Europa mission is assumed. The assumed mission consists of a cruise to the Jovian system and, after initial orbital insertion, go through a series of gravity assists prior to being captured into a circular orbit around Europa. The combination of mission trajectory and desired system characteristics lead to a set of baseline design objectives. Those that affect pointing include assuming that Opcomm is a replacement for an HGA, and that the initial checkout is expected 3 months after launch, which means the minimum distance to Earth where the lasercom subsystem would operate is at approximately 0.5 AU.

In terms of in-orbit geometry, at Jupiter the distance to Earth varies from 6.6E8 to 9.64 E8 km. (4.4 to 6.4 AU), and maximum range occurring during Earth daytime viewing conditions. Except during solar conjunction (when the SEP angle is small), and during opposition (when the SPE angle is small), the system should maintain sufficient downlink margin.

5. System Requirements

A set of System-Level requirements on the S/C were identified as the basis of the development. The pointing requirements are derived based on a set of assumptions listed below. Operationally, a typical mission will contain science observations, and communications with the Earth to transmit the scientific data. The amount of science that can be usefully gathered depends on the bandwidth available for telecommunications. During laser communications, the S/C is expected to have slow limit cycle motion, with deadbands typically 2 milliradians and typical angular rates of 5 to 20 urad/second, with micro-thruster firings at the end of each deadband cycle. Because the baseline tracking system provides only two-dimensional position knowledge, the third axis knowledge must be found elsewhere. Our approach requires frequent (1 update every 1 to 10 seconds) attitude estimates (say in the form of a broadcast quaternion) from the S/C ACS, including the twist axis knowledge. Twist is needed because of the up to 200 urad point-ahead angle due to two way light time. The S/C is additionally expected to keep the Earth within the FOV of the Opcomm telescope.

- Spacecraft microvibration environment shall have integrated amplitude less than 3 dB frequency less than vibration spectrum at the hardware interface
- Spacecraft shall maintain pointing accuracy better than 1 mrad, and average deadband cycle period than 20 urad/sec, provide attitude information to the Opcomm subsystem with attitude knowledge better than TBD [20] urad, and finally, the S/C attitude knowledge of Earth better than 1 mrad in all three S/C axes for acquisition.
- Uplink sequence tells which ground tracking station is used for pointing.
- The downlink shall have the Average Bit Error Rate (after error correction), and Frame Rejection Rate < 0.01 . Frames not rejected shall have bit error rate much better than 1 part in 10^6
- Opcomm subsystem shall be capable of acquiring the Earth and direct downlink signal when the Earth boresight falls within the acquisition field of view of 3 mrad, where the acquisition field of view is smaller than detector FOV.
- The Opcomm subsystem shall maintain pointing of the transmit signal during daytime reception with an loss due to pointing of less than 2dB.

- **Pointing Loss and Impact on Link Performance**

For optical links, the random pointing error results in variation of the downlink signal power. Because of the narrow transmit beamwidth, the downlink signal power is very sensitive to the transmitter pointing error. A large transmitter offpoint can lead to undesirable signal fade on the ground, and hence must be controlled.

2. POINTING ACQUISITION AND TRACKING

The pointing acquisition and tracking (PAT) problem is critical to the Opcomm subsystem implementation because of the narrow beamwidth of the transmit signal. Inaccurate beam pointing results in large signal fades at the receiving site and a severely degraded system performance. This problem is compounded by the fact that the amplitude of S/C platform jitters due to spacecraft deadband cycle and random vibration are much larger than the transmit beamwidth. As a result, a dedicated pointing control function needs to be an integral part of the lasercom subsystem design. The required pointing accuracy of the transmit signal is typically on the order of a few microradians for a diffraction-limited system. In contrast, the RF communication system pointing requirement is 0.1-0.5 degrees, several orders of magnitude less stringent.

This section provides a description of the X2000 Opcomm subsystem PAT function. The Europa mission provides the scenario for this study, but the analysis extends to other scenarios. A number of approaches --- described later in this section --- have been studied, and the strengths and flaws of each were analyzed, to finally arrive at the current baseline. Because of the desire to maintain a downlink independent of an uplink beacon, the acquisition and tracking strategy focuses on the use of passive references such as Earth and star images rather than an uplink beacon for celestial reference. The main technology issues have been straylight effects, pointing stability, Earth image signal strength, Earth albedo effects on measurement accuracy, and for the case of the Europa mission, radiation effects, and limiting requirements on the S/C.

1. Beam Pointing Requirements

For the link design, the required 3-sigma pointing accuracy is approximately $0.54 \lambda/D$ or, equivalently, $1.9 \mu\text{rad}$. Even at Europa distance, 1.9 urad presents a very small target for pointing the downlink. Shown in Figure AAA1 is a diagram showing the (3-sigma) error circle to point the downlink.

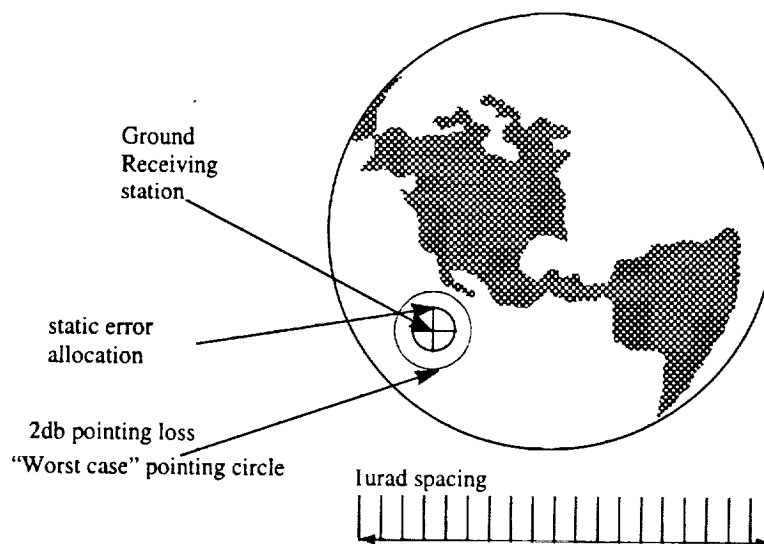


Figure AAA1 Diagram illustrates the pointing requirements for the Europa orbiter mission

2. Baseline Pointing Approach

The pointing acquisition and tracking (ACK/TRK) function performs the measurements and pointing control of the downlink laser signal from the spacecraft platform to the Earth-based receiving station. The main steps of this task are

1. S/C attitude measurement data is used to determine the initial pointing direction of the system, and then to seed the initial acquisition of the Celestial Reference (CR) Targets and determine the *twist* about the optical boresight
2. Acquire the Celestial Reference Target using a focal plane array (Celestial Reference Detector). This can be the Earth, stars, Moon, or uplink beacon signal from an Earth station.
3. Determine J2000 coordinates of the optical boresight based on knowledge of the **absolute location** of **Celestial References** (knowledge based on ephemeris) and measurements from on the Celestial Reference detector. This process combines image measurements performed at discrete sampling times t_k and the corresponding J2000 positions to determine the pointing of the Opcomm telescope with respect to inertial space. At the sampling times, attitude quaternion estimates ${}^J q_{meas}^{OCT}(t_k)$ are computed and used to update the telescope pointing knowledge.
4. Determine the desired direction for pointing the downlink in inertial coordinates, based on ephemeris, one-way light time, and Earth receiving station location.
5. Control the steering mirror to point the downlink laser to the receiving station. This pointing control loop compensates line-of-sight and Mirror jitter effects, caused by either the vibration of the platform coupling across the mechanical interface, or mechanical resonance of the structure excited by the mirror actuators.

Shown in Figure AAA2 is a functional block diagram of the acquisition and tracking concept. The Celestial Reference (CR) image is collected by the telescope and imaged onto the Celestial Reference active pixel sensor (APS) detector (Cel-APS). The CR detector provides sampling of the position at discrete times t_k . The measured position of the Earth (or other celestial objects) and its associated J2000 location are then merged with S/C attitude estimates to make very accurate estimates of the telescope line-of-sight via an attitude quaternion. With the attitude quaternion, the Earth receiving station location at the time that the laser transmit (Tx) beam arrives can be computed in J2000 coordinates, including offsets due light-time. The desired pointing direction can then be mapped into the transmit reference APS (Tx-APS) coordinates.

When the celestial reference signal is strong and the Cel-APS detector provides sufficiently high update rate, it is possible to achieve accurate control of the downlink pointing using the celestial reference alone. Downlink beam pointing is accomplished via a two-axis steering mirror located in the transmit beam path. Closed loop pointing of the mirror is achieved with the help of a second APS, called the Transmit Reference (Tx) APS. The Tx-APS measures the instantaneous deflection of the downlink signal relative to the telescope coordinates. The derived measurements are then used to close the mirror pointing control loop. Since the receive line of sight is not compensated, pointing jitter can be partitioned into the mirror jitter, which is the jitter of the mirror relative to the telescope line of sight, and the telescope jitter, which is the motion of the telescope body. Mirror jitter will be measured using the Tx-APS which images the downlink laser signal, while telescope (line of sight) jitter will be measured using the Cel-APS.

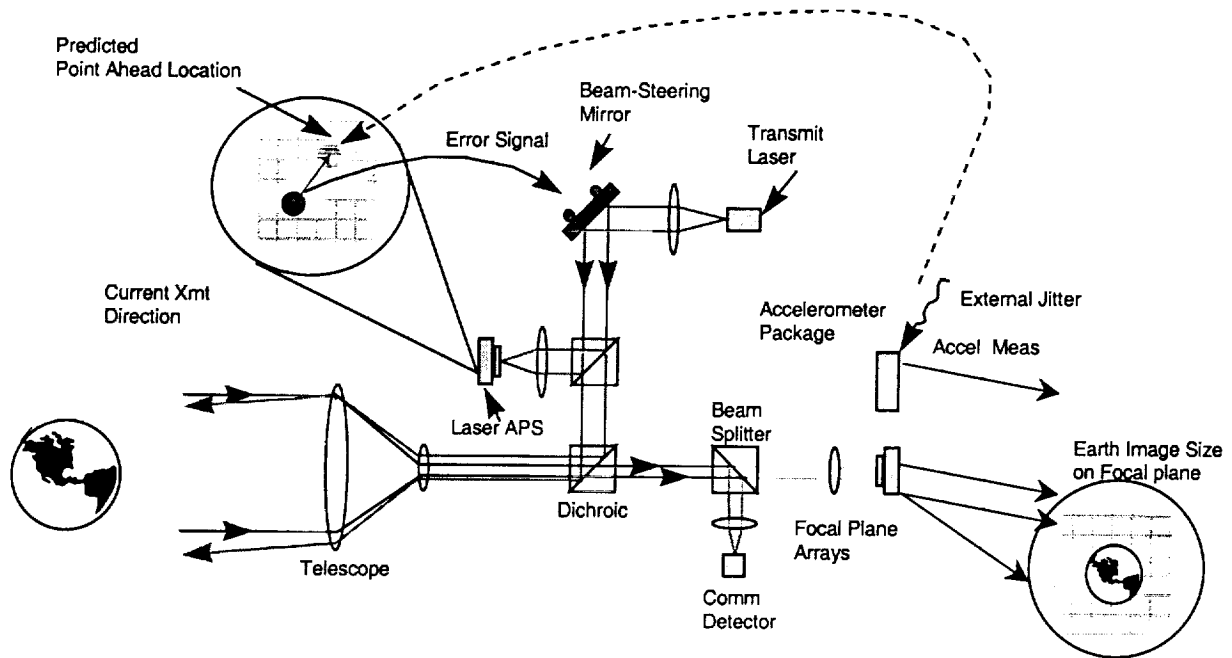
The baseline tracking approach will allow tracking using either an uplink beacon or Earth Image tracking. Beacon tracking will be used when the spacecraft is close to Earth and when the Earth image is too faint to track, such as when the Sun-Earth-spacecraft (SEP) angle is very high and the Earth appears as a crescent from the spacecraft.

While Earth image tracking is desirable because of its high brightness and importantly, does not require an uplink (which considerably simplifies link operation), Earth image tracking requires accurate compensation for centroid shifts due to Earth weather induced albedo variations. This problem is illustrated in Figures AAA3a through AAA3c. Figure AAA3a shows a Earth images taken by the Galileo spacecraft as it recedes from Earth. The image contains intensity variation due to presence of cloud pattern. The same image as would be seen through diffraction limited optics is shown in Figure AAA3b. The diffraction-limited point spread function reduces the image contrast significantly. Finally, at Europa distance, the image is only several pixels in diameter, and the detector pixel quantization complicating the image resolution, as illustrated in Figure AAA3c. Computing accurate centroids from the pixilated image presents a challenge to the design.

The Opcomm subsystem solves the albedo variation problem by performing periodic imaging of the Earth image with other celestial references -- such as the moon or nearby stars which have a more predictable distribution of light, and where the mapping from a centroid measurement to a J2000 location is only limited by straylight, noise, S/C jitter, and modeling error. Using accurate measurements of these celestial targets, the albedo offset of Earth can be accurately deduced.

When the celestial reference or uplink beacon cannot not provide sufficient signal for high rate tracking, inertial sensors (accelerometers) measurements are used to propagate the knowledge of the optical boresight at a higher rate in between Cel-APS updates. The inertial sensors measurements are integrated and combined with the CR target measurements to provide knowledge of the telescope pointing at high rate. The combination is used to determine the attitude quaternions at continuous times, ${}^J\mathbf{q}_{est}^{OCT}(t)$. This information is then used to compute the desired pointing direction. In this case, Mirror jitter will be measured using the reflection of the downlink laser, while telescope jitter will be measured using a combination

Figure AAA2. Tracking concept overview



of Cel-APS and accelerometers.

Hardware Assumed:

1. Reflective 30cm diameter telescope mirror, with multiple prisms, mirrors, etc
2. Steering mirror to direct the downlink Tx laser beam to the Earth. Commanding rates are 100Hz to 400Hz.
3. APS (Celestial Reference) with 7 -10 urad pixels to measure the Earth (or other target). Frame rates are 10 to 100Hz. A set of inertial sensors to propagate the attitude (from Celestial Reference APS).
4. One APS (Tx-APS) to measure a reflection of the Tx laser beam (Tx laser spot), reflected from the steering mirror assembly, to measure the pointing of the mirror relative to the S/C. Typical rates are 2000Hz.
5. Passive isolation of assembly from S/C -- This is not part of the baseline, except in those cases where a interface requirement to the S/C cannot be met. No particular design has been analyzed yet.



Figure AAA3a. Earth image as seen by the Galileo spacecraft as it recedes from Earth

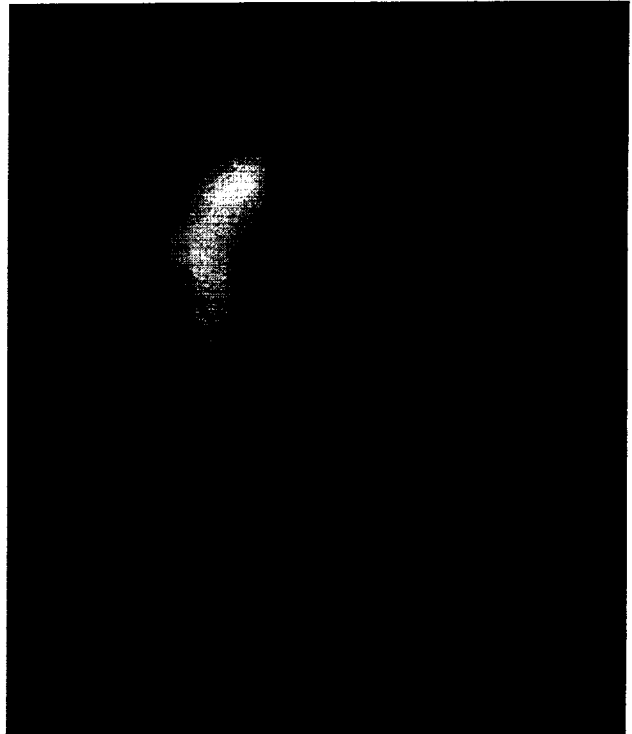
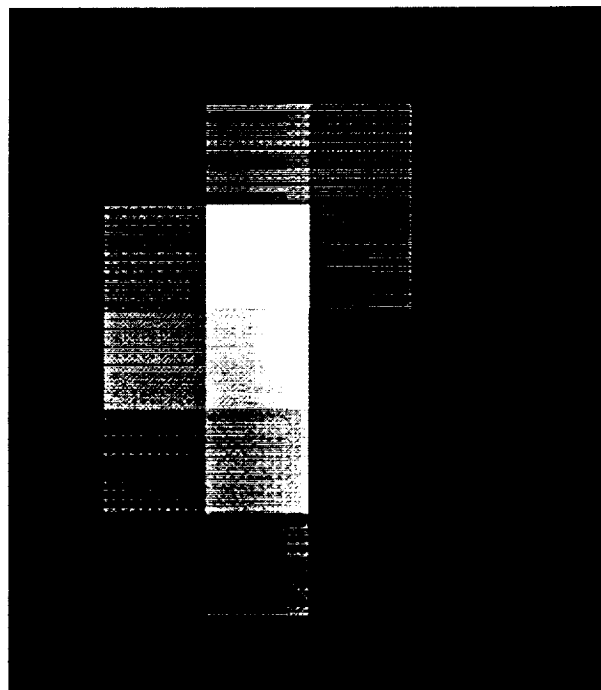


Figure AAA3b. Same image of Earth as seen through a diffraction limited optical system. The image blurring is due to the diffraction-limited spread of the receiver optics.

Figure AAA3c. Same image of Earth as seen through a pixelated detector with a pixel field of view of $3.5 \mu\text{rad}$. The proposed subsystem implementation requires detector pixel field of view of $7 \mu\text{rad}$ due to spacecraft deadband and available detector format



• Acquisition Strategy

While not expected to be as difficult as the tracking function, the acquisition function performs the necessary initial location of both the celestial reference targets and the transmit pointing direction. For acquisition in general, locating the targets to 1/2 pixel is sufficient to start the tracking process. Because of the narrow FOV, the acquisition process requires some initial a priori attitude information, in the form of an attitude quaternion estimate from the S/C ACS system, ${}^Jq_{SC}^{S/C}(t)$, which maps the J2000 frame to a predefined S/C coordinate frame. It is assumed that the S/C, based on attitude and ephemeris information, can place the required images (Earth, Moon, etc.) within the detector FOV. For acquisition, this ACS-supplied quaternion is assumed to provide at least 1 to 2 mrad accuracy in the Celestial Reference detector focal plane. More stringent **twist accuracy** is required from the S/C to achieve the current pointing requirement in track. In a high radiation environment, additional processing is needed. The acquisition process for laser beacon tracking is the same. For star tracking options, the process is similar, but requires multiple spots to be acquired and identified.

The baselined acquisition process include the following steps:

1. **Collect image frame.** For image contrast, the exposure times are 10ms to 1 second, barely saturating the Earth image.
2. **Scan Pixel Data for Earth.** This is a simple scan search, looking for images the size of the Earth.
3. **Generate Earth Location.** The centroid of the Earth is computed.
3. **Compare to S/C attitude.** The predicted location of the Earth should be within the S/C tolerances.
4. **Improve accuracy of measurement.** Once the Earth is located using smaller track windows, the time between pictures can be speeded up, the search area narrowed, and position computed to better than 1/2 pixel per axis.
5. **Locate other required images.** Once the Earth image is located, the attitude estimate is improved by merging the Earth measurement with the S/C quaternion. The Moon location, or any stars needed are then known to 20 urad (≤ 3 pixels), worst case, assuming 7 mrad FOV and 1 mrad 1σ twist error, and the Earth at an extreme edge of the FOV.
6. **Locate Tx Laser spot.** Here the only trick is to position the steering mirror near the desired pointing location. It is unlikely that the open loop pointing is more than a few pixels off; since the Tx spot location is on a separate detector.

• Tracking Strategy

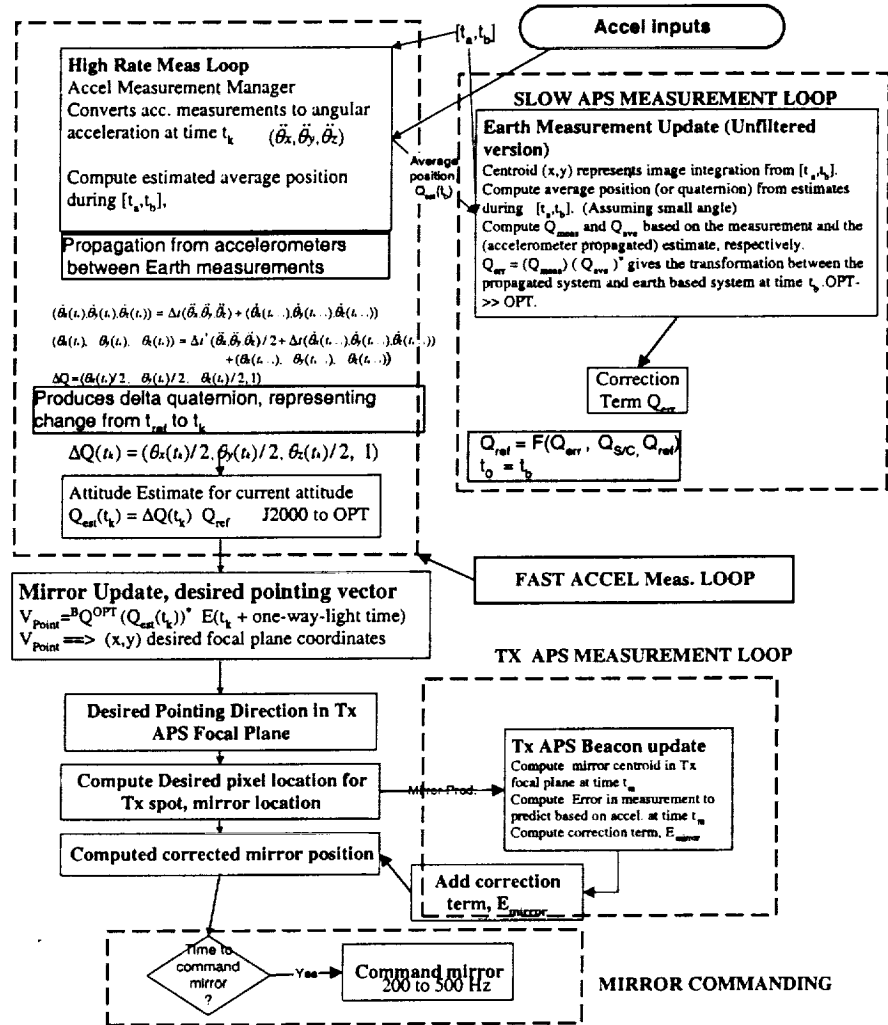
Once the acquisition sequence completes successfully, the Opcomm subsystem will make a transition into tracking mode. The tracking function measures the position of the Earth in S/C coordinates, and merges these measurements with S/C attitude estimates and the known J2000 location of the Earth. The location of the receiving station (also known in J2000 coordinates) is the desired pointing direction in the Tx-APS coordinates. The Tx-APS measures the actual position of the downlink relative to the telescope coordinates. The difference between the measured downlink direction and the desired pointing location is used as feedback on the mirror pointing control. Because of the potentially low signal power from the Earth measurements, inertial-sensors (accelerometers) are used to propagate the attitude knowledge between measurements. Finally, because of the variability of the Earth surface brightness (shown in Figures AAA3a - c), calibration of the effect of albedo on centroid is required.

Steps for Tracking

1. Command Tx steering mirror
2. Command Transmit Reference APS (Tx APS)
3. Compute point-ahead angle and location of Earth (Up to 200 microradians).
4. Inertial Sensor Update. Using inertial sensors outputs (accel's), update both the attitude estimate, and estimated point-ahead location of Earth
5. Compute desired location for laser spot on Tx APS.
6. Compute Tx centroid. Readout Tx APS, compensate pattern noise and pixel gain variations, compute centroid of signal from steering mirror.
7. Background compensation
8. Compensate for errors in mirror pointing.
9. Command Celestial Reference APS
10. Readout Earth image and/or Moon image and/or star images. Only the APS areas required for tracking are digitized and processed.
11. Compute centroid. Readout the OCT APS, compensate for pattern noise and pixel gain variations and compute image centroids.
12. Update Image background and straylight model, compensating for pixel non-uniformity with presence of high straylight..
13. Update Attitude Estimate. Merge S/C quaternion with compensated Earth/Moon /star measurements.

Functional flow of the tracking process is shown in Figure 5-5. The key pieces for the tracking process include the following steps. Note that this description does not include processing to handle the radiation SEU effects (only present in extreme cases).

Figure 5-5. Tracking process overview



The combination of accelerometer + celestial reference now is very similar to the typical attitude control system (ACS) gyro + star tracker system. The overall pointing control loop is depicted in Figure 5-6. This figure shows two measurement (feedback) loops in the control loop. One is due to celestial image tracking (slow) and the other is based on accelerometers (fast control loop). The update rate due to celestial reference image varies depending on Earth phase angle or uplink beacon power. It can be as low as 10Hz for 160 degree phase angle. For such cases, fast feedback loop is required to compensate S/C platform jitter (especially high frequency jitter). The output from the slow celestial sensor loop with point ahead estimate provides the reference point for fast feedback loop for downlink pointing. Over long duration, the receive image from the celestial reference is expected to wander. The accelerometer data will also be used to correct the uplink beacon location measurement on detector during long exposure time.

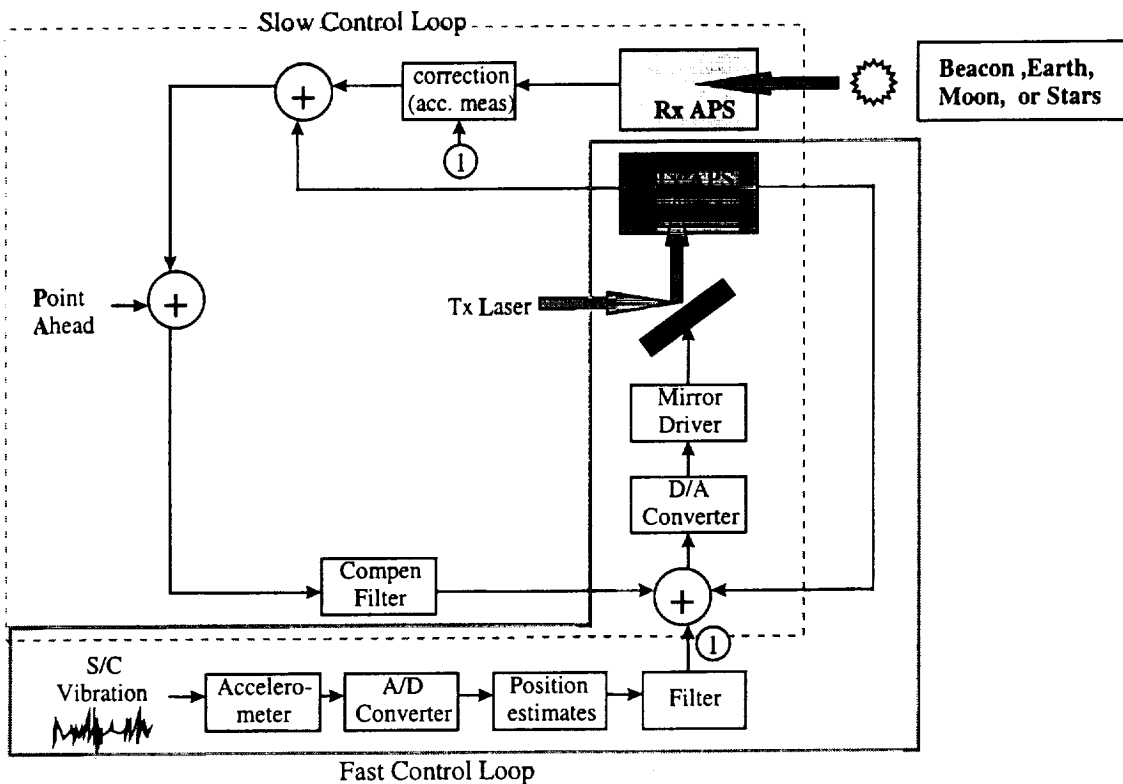


Figure 5-6. Accelerometer based Tracking Control System

1. Pointing Allocation

The overall pointing error budget of 1.9 μrad can be allocated to various pointing error sources. The overall pointing error of the subsystem includes a random contribution which quickly varies, potentially from frame to frame, and a static error term, which is slowly varying. The source of the random errors include sensor noise and control system error, and the sources of the static pointing error include the ephemeris error, fixed offsets due to algorithm error, and alignment errors.

Of the total error budget, 0.52 μrad ($0.15 \lambda/D$) is allocated to static sources, and 0.47 μrad ($0.13 \lambda/D$) 1σ to purely random sources. The error budget shown is the best guess for a Europa type mission. Other scenarios would result in a different partitioning of the error budget. A major portion of the error has been allocated to the static error in locating the geometric center of the Earth.

• Static Pointing Errors

The sources of the static pointing error include the error in estimating the Earth receiver position, the ephemeris error, error in computing the point-ahead angle, and alignment errors. The largest static error source is allocated to the error in estimating the geometric center of Earth using the image centroid ($0.12 \lambda/D$ or $0.42 \mu\text{rad}$). This error is due (primarily) to the uncertainty in image intensity distribution as a result of albedo, and will require periodic Earth-moon or Earth-star calibration to achieve the allocated pointing accuracy.

The boresight alignment error and errors due to thermal-mechanical distortion are the next largest sources of static errors ($0.2 \mu\text{rad}$ each). These sources can be controlled with careful optomechanical design and with careful alignment of the optics. Persistent static offsets can be removed by ground calibration.

- **Random Pointing Errors**

The two major contributors of random pointing error are the sensor noise and control error. The sensor noise include the noise introduced by the random photon noise (shot noise), detector noise and errors introduced by the pixel non-uniformity and spatial quantization. The control loop noise includes the uncompensated platform jitter and noise introduced by the control loop electronics.

Sensor Error and Noise

The sensor error allocation, which includes the detector noise equivalent angle and effects due to spatial non-uniformity of the devices, can be controlled. With a detector with reasonably low readnoise (10e/pixel/frame), the sensor noise contribution can be partitioned as follows:

1. **10,000 electrons/frame for the tracking reference image.** Based on APS design of 20e noise per pixel total noise (including A/D, accumulated dark current, A/D noise), we get approximately 0.14 to 0.17 urad error/per axis for a 5x5 to 7x7 pixel image, with no straylight. For a straylight rate of 2500e /pixel /frame, the NEA reaches 0.28 urad. At higher straylight levels, the frame rate will be reduced to increase required signal to noise.
2. **Background calibration required to approximately 0.15% for high straylight levels.** This level of background calibration allows tracking to approximately three degrees from the sun at full performance. The pixel to pixel variation in response is a large factor with high background.
3. **Defocus** of input signal by about 0.3 pixels 1σ for 25% fill factor APS, assuming Gaussian defocusing process. Minimum acceptable defocus will depend on the fill factor of the flight detector

Pointing Control Loop Noise

The source of control loop noise include the uncompensated S/C jitter, the accelerometer (inertial sensor) noise, and the noise in the control loop electronics. The dominant source of control loop noise is the uncompensated platform vibration. Analysis of the pointing control loop was performed to derive a pointing bandwidth (sensor update rate) requirements for the X2000 s/c by modeling the spacecraft vibration spectrum as in Eq. 1:

$$S(f) = \frac{A}{1 + f^2} \quad (1)$$

The model is based on the measured Olympus base motion power spectral density, and only the scale factor was varied. For Olympus, A=160, and the RMS pointing error over the entire spectrum is approximately 13.9 μ rad.

Using a mirror model with approximately 20 Hz resonance frequency, the effect of pointing update rate was analyzed. The result indicated that uncompensated error from the control loop is significant unless a high tracking update rate is available. Furthermore, the X2000 S/C needs to be quieter than Olympus S/C. At tracking update rates of 2 kHz and 4 kHz, the rms pointing jitter from base motion needs to be less than 2.9 urad and 3.8 urad, respectively. Note that it is expected that the X2000 s/c will have a quieter environment than Olympus because of the lack of large momentum wheels and the use of micro-Newton thrusters. Consequently, it is believed that although the jitter requirements are significantly less than that measured on Olympus, it can be met with the X2000 spacecraft. Since the S/C vibration spectrum is not yet known, the Opcomm design assumes that the platform jitter environment has total rms error is less than 2.9 urad, and that a 2 kHz tracking update rate is sufficient to limit the control system error to smaller than the pointing budget. If the S/C base motion jitter is larger, then a passive isolation stage must be used to reduce the effective line of sight jitter at the subsystem.

- **Celestial Optical References**

To achieve the desired pointing performance, the orientation of the telescope with respect to the Earth must be determined. This requires a high-accuracy tracking mode to measure a celestial target. The target can be an uplink beacon from Earth, the sun illuminated Earth, or other celestial sources such as the moon or bright stars, etc. Optical References are used to provide

absolute Line of Sight (LOS) pointing knowledge. From a Celestial Reference (possibly multiple) whose J2000 location is also known in telescope coordinates, and given a S/C to J2000 attitude estimate (primarily for twist about the boresight), the full telescope to J2000 coordinate transformation can be computed.

The optical reference target can be used to determine the line of sight of the optical system. This measurement is corrected for distortion, jitter, etc. The (estimated) J2000 location of the Earth centroid and the measurement are then used in the attitude calculation, which in turn is used to estimate where the receiving station will be when the downlink signal reaches Earth. The Earth, Moon, stars, or an uplink beacon are all possibilities to provide the optical signal for tracking. Except for the Earth, all these sources have a predictable light distribution where the mapping from a centroid measurement to a J2000 location is only limited by straylight, noise, S/C jitter, and modeling error. In the case of the Earth, it is additionally limited by the ability to compensate for albedo variations that are a function of weather.

Key considerations for the celestial optical reference include the following:

1. **Expected Signal Level and Track Rate:** how bright and how high a track rate can be achieved.
2. **Signal Availability -- Coverage:** When is the source available.
3. **Straylight Considerations:** How significant is the straylight contribution during usage.
4. **Target feature location knowledge:** How well do we know the location of what we are measuring - e.g., the brightness centroid of the Earth shifts due to albedo variations, contributing to error in the knowledge of the location we are measuring, contrasted to an error in the measurement process itself.
5. **Derived Point-ahead Accuracy:** How well can we determine the pointing for downlink.
6. **Expected signal wave-band and detector requirements.**
7. **ACS Requirements:** Attitude knowledge required from the S/C. Assumptions are that the S/C gives attitude knowledge better than 1 mrad about the telescope boresight, allowing a single target to be used for the tracking function. Needed are 1 mrad in twist for point-ahead, which is generally easy to achieve, and 160 μ rad twist for Moon-Earth tracking.
8. **FOV considerations:** How large should the FOV be. For optimal performance in Earth tracking, the FOV should be as small as possible while still containing the Earth during acquisition and deadband motion. Currently the combination of spacecraft deadband and pointing uncertainty appear to require about 5 mrad minimum FOV diameter. For star tracking, a wider FOV is better - to about 2 mrad.

Items 1-6 are discussed for Earth, beacon, and star tracking separately below. There are many possible target references with different degrees of applicability and difficulty. The baseline approach is Earth tracking, described after a brief discussion of phase angle effects on extended sources.

Image formation model

Phase Law. Shown in Fig. 5-7 is the viewing geometry for a spacecraft tracking the Sun-illuminated Earth (Moon). The intensity of the image collected from an extended object such as the Earth or Moon is governed by a phase law, which depends on the distance and viewing geometry parameterized by the phase angle (Sun-Earth-spacecraft angle). The phase law can be written as Eq. 2

$$V(r, R, \alpha) = 5[\log_{10}(r) + \log_{10}(R)] + V(1,1,0) - 2.5 \log_{10}(\phi(\alpha)) \quad (2)$$

where

$V(r, R, \alpha)$: Magnitude viewed at α degrees phase angle, distance R from the target, and the target at distance r from the sun.

$V(1,1,0)$: magnitude seen from 0 degrees phase angle, 1 AU from observer, object 1 AU from the sun.

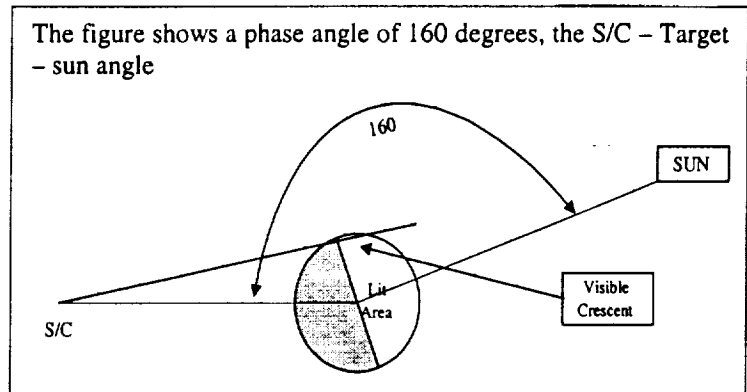
r: sun - object distance in AU.

R: observer - object distance in AU.

α : the phase angle, the sun-object-observer angle, (180 degrees is object in front of sun, 0 degree sun directly between observer and object, 90 degrees the object is half lit.)

$\phi(\alpha)$: phase law, $\phi(0) = 1.0$, $\phi(180) = 0$.

For a fixed aperture size, the phase law can be useful to compare the fully lit image (where the data is readily available) to different distances and phase angles. For the Earth or Moon, 1 AU from the sun, and distance R from the observer, and where R_0 is the distance used for the 0 degree phase angle flux calculation.



$$Flux(Phase = \alpha) = \left(\frac{R_0}{R} \right)^2 \phi(\alpha) \times Flux(Phase = 0) \quad (3)$$

The figure below (Fig 5-8) shows the fraction of the signal received as a function of phase angle, assuming models where the reflection is due to a Lambertian sphere, the Moon, and equal to the fraction of observable lit area.

Earth Image

Earth tracking is an attractive option. The Earth has a diameter of approximately 12750 km, and the Earth image is bright compared to other celestial sources. At low phase angle, Earth image provides sufficient photons for tracking at 2 kHz frame rate. There are, however, a number of problems associated with Earth image tracking. The signal from the Earth image has a wide variation, both in total and spatial distribution. The current best estimates show that the total signal follows a phase law between that of the Moon and a Lambertian sphere. There is some direct evidence the total Earth signal can be as bad as the Moon model under some weather conditions.

The following table shows signal versus phase angle estimates with no optics loss, and assumes the current low quantum efficiency (Q.E.) photogate APS design. It is hoped that the Q.E. can be improved by a factor of 3, and the number of electrons per second would scale accordingly.

Table 1 5-2 Estimated Earth signal, PGT APS, assuming 100% optical efficiency assumed for reference.

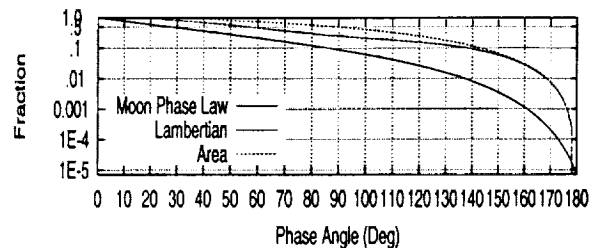
Phase Angle	Distance	Total Photons 400-900 nm	Photons, No phase law, no optics loss, PGT device	Photons, Lambertian Model, PGT device	Photons, Moon Model, PGT device
90	5.2 AU	5.7E9	7.0E8	1.7E8	6.2E7
160	4.3 AU	3.9E9	1.0E9	2.8E7	1.0E6
170	4.3 AU	3.9E9	1.0E9	7.0E6	2.0E5

Signal Availability: This is limited by the angular separation between the Earth and the Sun, and between the Earth and the Moon. Based on conic elements, the Earth as seen from Jupiter during the Europa mission period nearly always has sufficient separation from the Moon, since the Moon's orbit is inclined to the ecliptic by about 5 degrees. The angular separation between the Earth and the sun is limited by straylight considerations, rather than overlapping images.

Straylight Considerations: Straylight is a major concern. When the straylight rate becomes high, not only does the added photon noise create error, the pixel non-uniformity also becomes much more significant and requires pixel response calibration. Two degrees separation is the limited required from our study.

Figure 5-8. Phase Law

Fraction of Signal vs. Phase
Phase Laws For Moon, Lambertian Sphere, and Area



Target feature location knowledge: The albedo of the Earth shows significant variation with rotation and weather. For centroid tracking, this will cause a shift of the center of brightness, introducing a bias term.

Derived Point-ahead Accuracy: For the single Earth measurement, the expected point ahead accuracy is equal to the point-ahead angle times the attitude uncertainty (160 urad). The pointing ahead angle is typically on the order of 500 urad or less, and the combination of point-ahead and twist uncertainty gives an additional 0.08 urad radial pointing error.

Expected signal waveband and detector requirements: Earth signal (reflected sunlight) has about the same spectral distribution as the sun; with most of the energy in the 400-900 nm band. At long wavelength IR region, there is also the thermal emission from the 300K black body. The tracking detector for Earth image tracking needs to have spectral response from 400-900 nm.

Table 5-3. Star Signal strengths vs. magnitude

Star Magnitude	Flux with no optical loss	Flux 25% efficiency	Number of frames/sec
7.5	1.0E6	250,000	25 to 50
10.0	1.0E5	25,000	5 to 10
11.0	4.0E4	10,000	1 or 2

Stars and Star assisted

Coverage -- the availability of stars in the field of view-- is the key problem with star tracking. A 7.5 magnitude star is approximately as bright as the Earth at 160 degrees phase angle, assuming that the Earth brightness follows the same phase law as the Moon. An 11.5 magnitude star is as bright as the Moon at the same phase angle. The table shows examples of the expected flux.

Signal Availability: Figure 5-9 shows the number of days with less than 5 stars in the FOV for various FOV sizes and a limiting magnitude of 11. All stars included are taken from the Tycho catalog. The telescope boresight is assumed centered on Earth with no offset pointing. A magnitude 11 star should provide a 1 to 2 Hz tracking update rate. As can be seen, the number of stars available is highly dependent on the FOV size and the direction. As the FOV increases to more than 1.2 to 1.6 degrees in diameter, the star coverage becomes quite good. For FOV greater than 0.8 degrees radius, every such FOV has at least 5 stars with 11th magnitude or brighter.

The effect of reducing the field of view and cut-off magnitude is shown in Figures 5-10a,b and 5-11a,b. the coverage as a function of limiting magnitude cutoff for a 0.4 and 0.6 degree radius FOV is given, where the coverage is specified by the number of days with less than 1 and 2 stars in the FOV.

Figure 5-9. Total star coverage outage for an Europa mission.

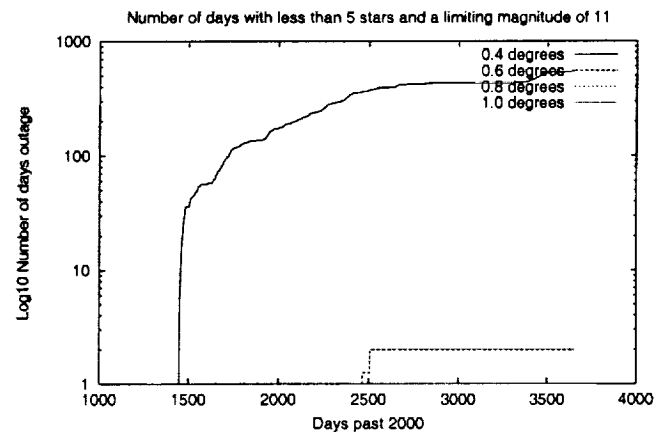


Figure 5-10a. Total days when no star brighter than the threshold magnitude is within 0.4 degree of Earth as seen from Jupiter.

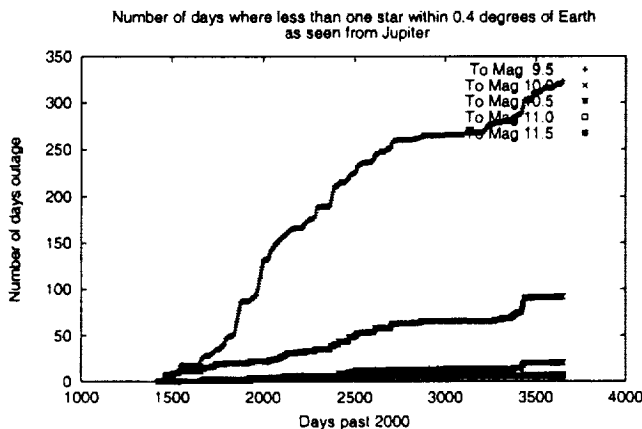


Figure 5-10b. Total days when no star brighter than the threshold magnitude is within 0.6 degree of Earth as seen from Jupiter.

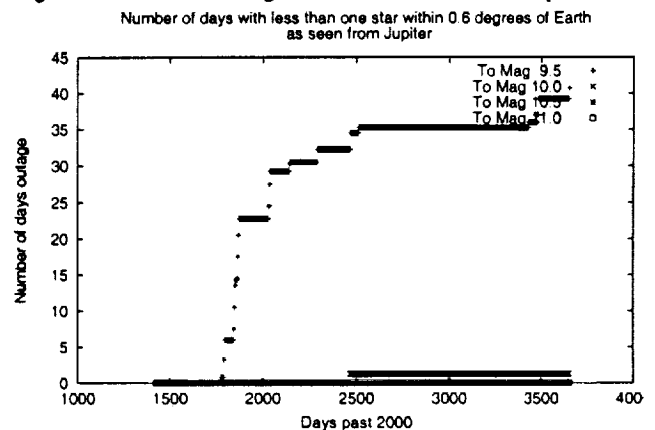


Figure 5-11a. Total days when less than 2 stars brighter than the threshold magnitude are within 0.4 degree of Earth, seen from Jupiter.

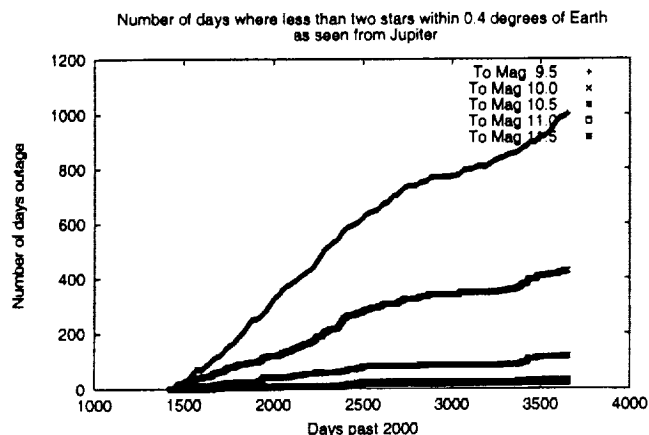
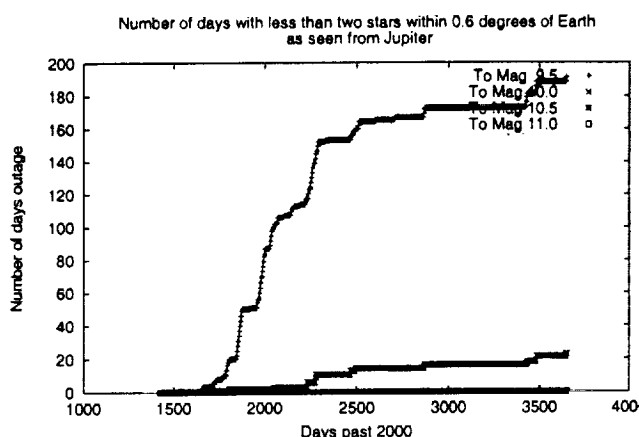


Figure 5-11b. Total days when less than 2 stars brighter than the threshold magnitude are within 0.6 degree of Earth, seen from Jupiter.



Stray-Light Considerations: Because of the dim signal and the broadband nature of the star signal, straylight (scattered sun light) is a major consideration. However, if offset pointing is possible, then much of the straylight issue can be avoided.

Target feature location knowledge: Stars in the Tycho catalog are known to about 25 milli-arcseconds (0.12 urad) and in the smaller Hipparcos catalog, to about 1 milli-arcsecond (0.005 urad).

Derived Point-ahead Accuracy: This is a tricky question to answer, because the star distribution is highly variable. Since twist accuracy times offset from the desired pointing location gives the pointing error, the final accuracy depends on where the stars are relative to the Earth point-ahead location. With multiple stars in the FOV, the twist accuracy should be better than 100 μ rad 1 σ about the boresight. If, on the other hand, offset tracking is used and the Earth is offset by 1 degree from the guide star, the point-ahead error would be 1.7 urad, well beyond our error tolerance.

Expected signal waveband and detector requirements: High detector Q.E. is required because of the low star intensity. Furthermore, star spectral distributions are widely variable and therefore the detector must have a wide bandwidth.

Uplink Beacon

Uplink beacon tracking is perhaps the most attractive option from the point of view of implementation. A laser signal presents a well-defined point spread function, and the very narrow bandwidth allows easier rejection of the background-scattered sunlight. The problem with uplink beacon tracking for Europa is the amount of available power. At Europa (6 AU) using a 500 W uplink laser operating at 0.532 μ m, the number of photons received at the tracking detector is approximately 2.3×10^5 photons/s. Even with aggressive assumptions on the uplink power and beamwidth, the amount of signal not expected to exceed 5×10^5 photons/second. Compared with the required signal power of approximately 10,000 detected photons/frame, it is seen that uplink beacon tracking alone cannot provide the tracking bandwidth required to control the pointing error.

Signal Availability: Signal availability is limited to when the transmitting station can be seen from the spacecraft, and when the weather conditions permit --- this is one of the key limitations.

Straylight Considerations: Straylight can be reduced, using a narrow band filter. It appears (this needs to be verified) that a 0.2nm to 1.0nm wide filter can be used, reducing the straylight contribution. A narrowband filter is needed to filter out both the sun straylight and the Earth background. The Earth at zero phase angle, when seen from Jupiter, has a similar intensity and spectral distribution as that of a 0th magnitude black body. Using the blackbody signal model shown in Figure 5-12, the Earth at 0 degree phase angle and 5 AU distance generates about 6×10^6 photons/nm/second.

Target feature location knowledge: By tracking an uplink beacon, the knowledge of the ground station location is nearly perfect. There is difficulty in distinguishing the beacon location from the Earth background. Based on the blackbody model shown in Figure 5-12, the Earth at 0th magnitude (0 degree phase angle seen from Jupiter) produces at 532 nm approximately 6×10^6 photons/nm/sec at the primary. Optimistically at 6 AU, the incident photon flux from a 500 watt uplink laser operating at 532 nm is 2.3×10^5 photons/seconds (some estimates show this 3 times less). The laser output is clearly overwhelmed --- especially considering the variability of the Earth signal. Even with a narrowband optical filter of 0.2 nm bandwidth, the background photon flux is still 5 times higher than the beacon signal strength. To perform beacon tracking, therefore, accurate calibration of the Earth contributed background may be required. A practical limit for the beacon tracking will be at a SEP angle of 30 degrees when the Earth contributed background drops.

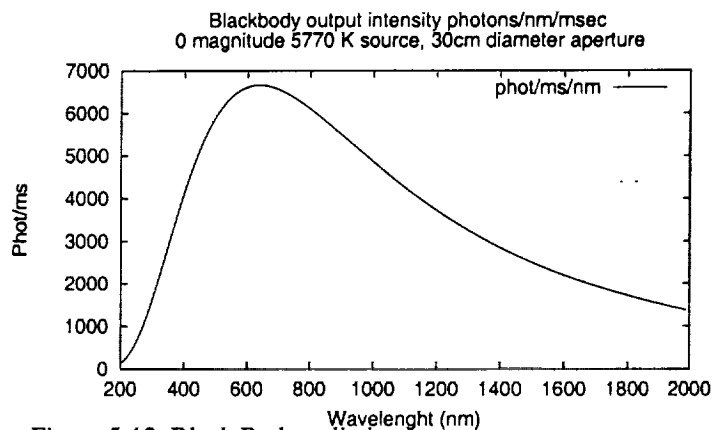


Figure 5-12, Black Body radiation curve

Above 90 degrees phase angle, the Earth background becomes less of a problem and beacon tracking becomes more feasible. Depending on the phase model, the Earth background is about 10-25% of the beacon signal strength. At very high phase angles, (>160 degrees), the Earth background is (depending on the model assumed) on the order of 5×10^3 incoming photons/nm/second. Here the flux from the laser beacon is significantly larger; eliminating any image induced bias.

At smaller phase angles, there can be sizeable centroid error from the Earth background. Given two centroid measurements -- (x_L, y_L) for the beacon and (x_E, y_E) for the Earth image, with intensities B_L for the laser and B_E for the Earth, (the intensities are measured in the waveband) the centroid of the system is shifted from the uplink beacon source by an amount

$$(x_L, y_L) + \frac{B_E}{B_E + B_L} (x_E - x_L, y_E - y_L) \quad (4)$$

With an Earth image that is 20 urad wide, the separation between the Earth and beacon centroids $(x_E - x_L, y_E - y_L)$ could be as large as 20 urad. Considering the brightness ratio, $B_E/(B_L + B_E)$, a 1:10 ratio would cause a 2.0 urad shift in the estimated centroid location. This is much too large an error. A 1:100 ratio is acceptable in this case, since the laser spot would be located to 0.2 urad, approximately the error allocated for measurement error. Because of the possible atmospheric-induced intensity fluctuations of the laser signal, and the variability of the Earth background intensity, knowledge of the intensities values for B_L and B_E could have significant errors. The centroid location for the illuminated portion of the Earth, (x_E, y_E) is also susceptible to variation in Earth intensity (albedo variation). Some of this error can be taken out by knowing the position of the laser beacon is relative to the lit Earth, but there still will be residual errors.

Possible Compensation. Because of the predictability of the laser spot shape, a better centroiding algorithm -- such as the maximum likelihood algorithm or some other model based algorithm -- might yield better results by working on the part of the signal away from the lit limb, but this has not been analyzed. Acknowledging some obvious operational complications, if the uplink beacon could be initially strobed at slow intervals, Eq (3) could be calculated with both $B_L = 0$ (laser off), and using the laser signal. The change in brightness could be used to determine whether the laser image was combined in the signal, or the image included the Earth only. Knowing one of the terms in Eq. (3), as well as the sum gives a more accurate location of the point (x_L, y_L) . A procedure like this could also be used as part of a calibration procedure to attempt to correct for Earth albedo. For the case where the Earth is large, but less intense than the laser spot at the relevant wavelength, the expected size in pixels of the laser spot can be used to limit the centroid window area, and the contribution of the Earth image.

Derived Point-ahead Accuracy: Speed of light considerations are the same as for the Earth only; the results are the same as for the Earth and Moon alone.

Expected signal waveband and detector requirements: Narrow band filters are required, and the detector should have high Q.E. at the wavelength of the laser.

Summary of possible pointing targets

Obtaining an accurate celestial reference is a critical step in pointing the optical downlink. The celestial reference target can be an uplink beacon from Earth; the sun illuminated Earth, or other celestial sources such as the moon or bright stars, etc. Shown in Table 5-4 is summary of various tracking approaches considered for X2000. The baseline approach finally adopted is Earth image tracking. The Earth image provides a bright reference that is close to the receiving location. The Earth albedo variation is calibrated with occasional Earth-moon or Earth-star image tracking. At high phase angle when the Earth image is dim, uplink beacon tracking can be used to provide the accurate reference.

Table 5-4 Comparison of various tracking approaches

Approach	Requires	Limitations/Benefits	Sun Geom Limited	Inertial Sensors Req.
Beacon Tracking	Requires Uplink Signal	Only Applicable at close (1AU distances) without Inertial Sensors	Yes	Not Near to Earth
Earth Only Tracking	Albedo variations cause center of brightness (c.o.b) shifts. Calibrate /live with offset error	At close distances, edge tracking can provide updates, or defocus downlink	No	High Phase Angles
	At 0 phase and 1AU Earth has magnitude -3.8	Signal varies with phase angle/distance ~40x worse at Pluto than at Jupiter		
Earth Moon Tracking	Moon has predictable Albedo, and can help determine albedo offset	Degraded with Earth-Moon have large separation or too close	Yes	High Phase Angles
	Error of Moon Measurement induces pointing error bias	Signal varies with phase angle/distance ~40x worse at Pluto than at Jupiter		Long Moon Exps
	Moon 40 times dimmer than the Earth	Moon requires 40x more exposure time		
Only Star Tracking	Requires Stars to be in FOV	Low Signal	No	Yes
	Requires Inertial sensors			
	Pointing based on J2000 coordinates /attitude	Track Signal not a function of distance		
	May Require Offset Pointing for Straylight Rejection	10-20 Hz for 10 th mag stars, possibly 10.75 Mag with better APS QE		

Notes:

1. Except for the Star Tracking option, S/C Attitude is required for downlink pointing (Boresight twist is needed for the downlink pointing)
2. For Star Tracking, multiple stars expected to be in the FOV; the point ahead angle determined from ephemeris and star measurements.
3. All options have outage at superior conjunction.
4. Star Tracking option will probably require larger FOV to guarantee coverage, to possibly as large as 2 degrees diameter.
5. Current low noise APS fill factor design presenting problems for both photometry and pixelization effects.
6. For comparison purposes, it appears that the worst case sun contribution at 2 degrees offset yields the equivalent of 10.5 magnitudes /7microradian pixel. For a star of magnitude 10.5, with a 5x5 centroiding area and total star signal of 5000e, the noise contribution due to stray light would be approximately $\sqrt{2} \cdot \sqrt{S + 25 \cdot S} / S = 0.1$ pixels. PAT Design Considerations I - Measurement Accuracy and Noise

Inertial Sensor-Based Pointing

Given that most celestial sources don't provide the amount of incident flux for optical only tracking, alternative means of providing the tracking update rate is necessary. Note that even though Earth image tracking at low phase angle appear to be possible, it has a limited application range and will require extensive development of the tracking algorithm to account for the albedo variation.

As a result of the limited study (because of the low image signal, and potential S/C jitter), inertial sensors have been added to assist tracking. The inertial sensors provide short term attitude propagation, and can reduce the required celestial measurement frame rate from 1000Hz to as low as 10Hz. The inertial sensor-based angle measurements can be accomplished using either linear accelerometers or angular velocity sensors (gyros) or angular rate sensors., with the key issues being mass and power.

6. Summary of Pointing Approach and Discussions

From the analysis done, using passive isolation, accelerometers, and a 10Hz to 100Hz Earth tracking loop, albedo offset calibration (by any of a number of methods), the overall absolute pointing accuracy can be achieved over a wide range of time when the angular position of Earth image is not close to the sun.

The Earth albedo issue is avoided by adding auxiliary measurements to calibrate the offset of the Earth geometric center location to the position measurements of the Earth image. These auxiliary position measurements include taking occasional Moon or star measurements. Both Moon and stars have much more predictable light distributions and the position of these images can be estimated very accurately. However, these images generally are *much* dimmer than the Earth and cannot provide sufficient frame rate for attitude updates. Inertial sensors allow a wider range of measurements to be used, including the possibility of using an uplink laser beacon from the Earth, either as an independent approach for tracking, or for special cases, to provide additional tracking information for when the Earth is at high phase angles, even at the distance of 5 to 6 AU.

Future possibilities are star tracking only options with high accuracy star tracker measurements and inertial sensors capable of propagating attitude for ten's of seconds instead of tenths of seconds; this would allow 8th to 11th magnitude accurately known Tycho catalog stars to be used as celestial references.

A second APS was added to provide feedback from the steering mirror. The second APS was needed because of the vastly different frame rates that can be expected from the Tx mirror loop (2000KHz) versus the frame rate from Earth tracking (as low as 10Hz). Current APS designs do not have separate exposure durations for different windows ---in fact, current JPL designs only have one window. The two independent APS detectors allow for this dual frame rate mode. This may be revisited as the APS technology matures, and allows for separate window/integration times.

Given current specifications, to meet requirements with 7 microradian pixels.

1. **10,000 electrons/frame for the Earth's image.** Based on APS design of 20e noise per pixel total noise (including A/D, accumulated dark current, A/D noise), we get approximately 0.14 to 0.17 urad error/per axis for a 5x5 to 7x7 pixel image, with no straylight. For a straylight rate of 2500e /pixel /frame, the NEA reaches 0.28 urad. At straylight levels higher than this, the frame rate will be decreased to increase the signal in order achieve the required signal to noise.
2. **Accelerometer accuracy to 0.5%.**
3. **10 Hz frame rate using accelerometers.** Current analysis for accelerometers shows that using 5Hz to 10Hz tracking updates from the Earth target meets pointing requirements, assuming full accuracy tracker measurements.
4. **Feedback on steering mirror position.** Feedback from the steering mirror is required at 2000Hz to determine the pointing of the steering mirror in telescope coordinates. A combination of mirror jitter and errors between the commanded position and true position force sampling at the full pointing bandwidth.
5. **Background calibration required to approximately 0.15% for high straylight levels.** This level of background calibration allows tracking to approximately three degrees from the sun at full performance.
6. **Compensation for Earth albedo** to locate the center of the Earth to better than 0.42 urad worse case, radial.

Other approaches that have been considered and not baselined.

1. **Optical Image Tracking without inertial sensors:** The major drawbacks for optical tracking only are signal level and detector technology. At a distance of 5AU, the Earth at high phase angles becomes so dim that even with a 30cm collecting aperture, the frame rate achievable may not exceed 10 to 50 Hz, well below that needed to meet the pointing goals. At close distances to the Earth (such as at Mars), or at some range of phase angles, optical tracking may provide high enough bandwidth without the use of inertial sensors.
2. **Common Mode, Stabilized line of sight for tracking.** Currently not part of the baseline, but this is still being evaluated; this will not increase the maximum bandwidth, but may allow tracking on dimmer targets and provide additional some common mode rejection of pointing and measurement errors. The same signal dynamic range issue still exists. This approach can take out higher S/C deadband rates.

3. **Earth Tracking Only.** While Earth can provide a strong signal source, albedo can yield a large centroid shift, especially when the Earth is less than 3 pixels across. At Jupiter, the worst case allowed pointing error is 1.9 urad, less than 1/10 the Earth diameter. The error allocation due to albedo shift is less than 1/40 the diameter (the error allocation was made as large as possible). Reflection from clouds and ice can be many times brighter than from ocean and some ground. The range of albedo extremes is 0.05 to 0.85.
4. **Uplink Beacon Tracking.** Inside (TBD) AU and using narrow band filters, tracking an uplink appears to be a strong candidate. Given an expected 100 watt uplink laser, at Europa distances and at high phase angles, there is a wide range of feasibility where the Earth's signal is not overwhelming. The difficulties are that very narrow filters may be needed (1 Angstrom) and operational approaches described later. Higher power laser beacons are probably needed.
5. **No passive isolation.** Without passive isolation, knowledge and control requirements are likely too stringent. Passive isolation can be eliminated if certain interface requirements to the S/C can be achieved, or fast frame rates attained.
6. **Active isolation and separate telescope platform.** A very good option for a S/C with a high power and mass budget. Active isolation has been successfully used on space missions, unacceptable for low power/low mass options.
7. **Single APS for two input channels** was not taken because of requiring two separate frame rates. Currently it is easier to implement two APS's rather than a dual window, dual exposure time APS. A single APS still may work if the signal from the Earth allows for high frame rates, say 500Hz or faster, with the Tx reflection signal sampled at 2000Hz . If the required frame rates are closer, digital pixel summation of the Earth images can be used to construct good images.

• Concerns and Open Areas

The biggest unknown design driver is the effect of S/C induced jitter (accelerations) in the pointing. Requirements on accelerometers and control bandwidth are due to the unknown jitter spectrum; however, this avoids tough requirements on the S/C dynamics. Additionally, passive isolation is being seriously considered to reduce the high frequency jitter. CPU load will need to be evaluated as the processing complexity increases.

As a result of this study, the key concerns and open areas are

1. Image background calibration required to 0.15% for straylight compensation, essentially separating the contribution from the sun and the target. Using a conservative estimate for surface cleanliness, scattered light will be about 10^{-2} sr^{-1} at 3 degrees, depending on angle, with a slope of 1.3 and varying slowly with wavelength. Scattered light per pixel will be roughly 5×10^{-13} of the incident sunlight, assuming a 7 μrad pixel FOV.
2. That the APS for the steering mirror achieves 2KHz frame rate (windowing) without degradation in the signal.
3. Heavy radiation environments -- *Open*.
4. Alignment with the S/C and negotiating attitude updates from the S/C at the required accuracy -- *Open*.

3. OTHER HARDWARE REQUIREMENTS

APS Focal Plane

There are two APS in the current system baseline; a celestial reference detector which images the tracking source, and a transmit reference detector which measures the pointing direction of the downlink signal. A list of the key APS requirements is shown in Table 7-10. The celestial reference is intended to be a photo-gate APS, taking advantage of the low noise capability, and the transmit reference APS can be implemented using the photodiode APS technology. Both APS's are required to have ADC capability. Note that even though the table showed two different detector specifications, eventually it is intended to develop a single, large format (1024x1024) detector for use in both applications.

Table X2000 Optical Communications Subsystem –
Pointing related Focal Plane Array Requirements

APS Detector	Celestial Reference	Mirror Reference
Single window update rate	~100 Hz for 30X30	> 2 kHz for an 8X8
Format	1024 x 1024	1024 x 1024
Pixel Type	Photo-gate	Photo-diode
Ave. QE (500 to 800 nm)	25 %	40 %
Full Well	> 50,000e	300,000e
Read Noise	< 5 e	40 e
Dark Current (@ 300 K)	<2500 e/s/pixel	<10000 e/s/pixel
Dark current uniformity	2 % RMS	TBD
ADC Conversion Rate	> 2 Msps	> 2 Msps
ADC bits (programmable)	5 e/step, 10 bit	5 e/step, 10 bit
Function/Control		
Multiple Window	Read and Reset Each Window	

Fine Steering Mirror

Since the precision beam pointing control requirement is much smaller than the spacecraft deadband cycle, an internal beam steering mechanism is needed to maintain downlink pointing independently. Furthermore, because of the microvibration expected, the beam steering mirror needs to provide a sufficiently high control bandwidth. The purpose of the fine pointing mirror is to provide beam steering capability without the need to move the entire telescope using gimbals. Instead, a small, movable mirror located in the aft optical bench can be servoed to provide downlink pointing.

4. SUMMARY

The design of an Europa-Orbiter mission provided a realistic assessment of the complexity for an operational optical communication system. The study showed that for an optical communications subsystem, considerations of mission coverage, wavelength selection, stray light, and beam pointing drive the system design, in addition to the traditional design drivers such as mass, power, and thermal issues. More detail is included in CCHEN.

Beam pointing and tracking is accomplished using Earth Image tracking with occasional calibration using the Earth-moon or Earth-star images. At high phase angles when the Earth image does not provide sufficient brightness for high rate tracking, inertial sensors (accelerometers) measurements are used to propagate the knowledge of the optical boresight at a higher rate. The inertial sensors measurements are integrated and combined with the celestial measurements to provide knowledge of the telescope pointing at a higher rate needed for closed-loop downlink control. Additionally, uplink beacon tracking may be required to support pointing at short range and during opposition when Earth image alone does not provide sufficient signal power for tracking. The Earth tracking concept allows the Opcomm subsystem to point the downlink signal without the need of an uplink signal, thus improving the link availability, and because Earth's high brightness (over most of the orbit period) and the angular proximity of Earth intensity centroid to the receiver location.

The challenges of Earth image tracking include the unknown Earth albedo variation due to cloud coverage and the solar stray light. The albedo variation problem is handled by performing periodic imaging of the Earth with other celestial references -- such as the moon or nearby stars, which have well defined intensity patterns that allow accurate measurements of their position and can be used to calibrate the albedo induced offset of the Earth.

Because of the low Sun-spacecraft-Earth angle expected throughout the mission, stray light control is important. At the low Sun-spacecraft-Earth angle the subsystem is intended to operate (2 degrees from Sun), both optical surface quality and cleanliness need to be controlled to ensure low scattering of incident sunlight.

7. Open Issues Not Yet Addressed

Although the design effort attempts to provide a conscious effort in addressing most of the known problem, Time and resource constraints have limited the scope of the study. As a result, a number of open issues still remain. These are

1. Trade off of mission complexity: This is perhaps the most important work to be completed. Based on the design study, it is seen that the Europa mission coverage and environmental requirements drive the design of the Opcomm subsystem. A reduced set of mission coverage requirements may lower the system complexity and hence cost.
2. Platform jitter consideration: Platform jitter drives the required tracking bandwidth and hence the design of the acquisition and tracking concept. If the platform jitter is significantly lower than modeled, a less complex pointing concept may be employed. If the contrary is true, then passive isolation may have to be employed to reduce the amount of vibration coupled into the subsystem.
3. Radiation issues: The component /design identified have not addressed the radiation sensitivity issue. Aside from the electronic parts issue (including the detector array), the optical design may be affected by the radiation issue as a mostly reflective design is needed to reduce the scintillation noise from radiation.

5. ACKNOWLEDGMENTS

The research described in this report was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.